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LONG-PERIOD SEISMOLOGICAL RESEARCH PROGRAM

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13. ABSTRACT

A technique for studying the focal mechanisms of small magnitude events at teleseismic distances was developed. By comparing observed amplitudes of long-period Rayleigh and Love waves with radiation patterns of focal mechanisms consistent with the previously determined tectonic regime of a certain region, it is possible to discriminate between different types of mechanisms on the basis of signals received at a very limited number of stations. Using only surface wave data from the high-gain station at Albuquerque (ALQ), it was demonstrated that 60 swarm-type events in the northern Gulf of California occurred on a transform fault and were characterized by strike-slip faulting. Preliminary results from applying this technique to several central Asian earthquakes which appeared explosion-like on an M_s-m_b plot indicate that this method may be a useful tool for discrimination of anomalous events.

The detection capabilities of the VLP station were evaluated using the special listing of events during the International Seismic Month. Surface waves were observed for 90% of the reported events of m_b 4.6 or greater. Half of the unobserved events were due to masking by the coda of earlier larger events. For 10% of the events observed at deep stations, only Love waves were observed. Surface waves with periods between 30 and 50 seconds were observed more often than surface waves with periods near 20 seconds, indicating the importance of the window in the spectrum of earth noise centered at about 40 seconds.

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SUMMARY

During the past year our research effort encompassed several different seismological topics utilizing data from the high-gain seismograph stations. In particular research was initiated on a promising long-period discriminant that may be especially applicable to events in central Asia. This discriminant involves a comparison of observed Rayleigh-to-Love (LR/LQ) wave amplitude ratios with expected ratios for events in a region of known tectonic framework. On the basis of preliminary results it appears that this surface wave technique may prove helpful for discrimination of so-called anomalous events (i.e., earthquakes that plot in or near an explosion population on an M_s (Rayleigh) - m_b basis).

The special cooperative study to determine the approximate surface wave detection threshholds of the high-gain stations, using the International Seismic Month (ISM) listing as a data base, was completed. The most significant result of this study was that surface waves were observed at one or more high-gain stations from 90% of the reported events of m_b 4.6 or greater and with focal depths $h < 100$ km.

Other investigations completed during the past year include a study of pulse distortion and Hilbert transformation in multiply reflected and refracted body waves, and a comprehensive analysis of long-period earth noise.

I. STATION MAINTENANCE

During the past 12 months of the subject contract the high-gain station at Ogdensburg, New Jersey (OGD), was maintained in constant operation. The analog (seismograms) data were complete for the entire

year. A problem with the zero level of the ADC unit in the digital data acquisition system was corrected by Lamont personnel. This problem resulted in only minimal (two weeks) loss of digital data. A special air conditioned room was constructed on the 1850' level of the mine observatory. This room is 12' long, 5' deep, and 8' high and houses the digital magnetic tape recorder. Controlling the environmental temperature, humidity, and dust content in this manner should ensure continued dependable operation of the digital tape recorder. Seismograms and magnetic tapes from OGD through November 1973 were forwarded to Asheville, North Carolina, for microfilming, and Seismic Data Laboratory in Alexandria, Virginia, respectively. As of December 1973 and continuing to the present time (14 June 1974 as of the writing of this report) both the seismograms and digital data from OGD are shipped to the Albuquerque Seismological Center in New Mexico.

II. RESULTS OF THE DATA ANALYSIS

A. Focal Mechanisms of Small Magnitude Events:

Tatham and Savino (1973) reported on a surface wave technique for studying the focal mechanisms of small magnitude events at teleseismic distances. This technique is now being applied to events in central Asia and may prove to be important to the discrimination between earthquakes and underground explosions in that region. In particular, by considering both Rayleigh and Love waves, we may be able to properly classify as earthquakes occasional small events that occur in certain regions of central Asia and that plot in or near the explosion population on an M_s (Rayleigh)-m_b basis.

The method employed by Tatham and Savino (1973) consists of comparing observed amplitudes of long-period Rayleigh and Love waves with radiation patterns of focal mechanisms consistent with the previously determined tectonic regime of a certain region. It is important to note that in using this method we do not determine focal mechanisms, per se, but rather discriminate between different types of mechanisms thought to be prevalent in a region.

In the study of Tatham and Savino (1973) the relative amplitudes of Rayleigh and Love waves with periods between 10 and 50 seconds were determined for some 60 swarm-type events, assumed to be shallow ($h < 15$ km), that occurred near the Delfin basin in the northern Gulf of California. These surface waves were recorded at the new high-gain station at Albuquerque, New Mexico (ALQ). The bathymetry and seismicity of the northern Gulf of California suggest that faulting is occurring at short spreading centers (dip-slip faulting) and along transform faults (strike-slip faulting). The radiation patterns for Love and Rayleigh waves corresponding to the above faulting patterns for the northern Gulf of California are schematically illustrated in Figure 1. All of these patterns were computed assuming double-couple sources and shallow focal depths. The position of the nodes in the radiation patterns for strike-slip faulting are independent of focal depth, but there are changes in the absolute amplitude of the lobes, especially for Rayleigh waves, with variations in focal depth. The dip-slip radiation patterns are for a pure dip-slip mechanism with the fault plane 15° from vertical and zero focal depth. It is important to note that these dip-slip patterns change significantly with increasing focal depth, even to a depth as shallow as 33 km. That is, as depth increases for dip-slip mechanisms, the

number of nodes and the number and amplitude of lobes, changes. However, the amplitudes of the surface waves, especially Rayleigh waves, tend to decrease as depth increases, an effect that is especially pronounced for these dip-slip mechanisms. Further, the amplitudes of surface waves generated by near-vertical dip-slip faulting tend to be small at all focal depths. The reader is referred to the paper by Tatham and Savino (1973) for more detailed arguments concerning the focal depths of the swarm events included in this study.

The near optimum azimuthal position of the high-gain seismograph station ALQ, with respect to the radiation patterns shown in Figure 1, provides for the possibility of discriminating between the two possible focal mechanisms assumed for the northern Gulf of California. For normal faulting on a spreading center, surface waves radiated on the azimuth of ALQ should be weak and of approximately equal amplitude distribution in both Love and Rayleigh waves. For strike-slip mechanisms, Love waves should be of much greater amplitude than Rayleigh waves. Figure 2 (a-b) shows examples of the relative excitation of Rayleigh and Love waves by two swarm events recorded on the 3-component high-gain seismographs at ALQ. Figures 2a and 2c show the three orthogonal components of each record segment normalized to a common magnification for each event. It is especially evident that the horizontal Love-wave motion dominates over the vertical motion. Further, the observed vertical motion does not have the character of fundamental Rayleigh waves, and may possibly be due to higher modes. Figures 2b and 2d illustrate the result of a rotation of the horizontal components into equivalent radial

and transverse traces. Here the Love-wave motion of the transverse component is clearly much greater than the Rayleigh-type motion that would be observed on the vertical and radial components. In addition, the radial motion shows the same lack of fundamental Rayleigh-wave character as that observed for the vertical motion. These few examples demonstrate that Love waves are indeed the dominant surface waves observed at ALQ and from this it was concluded that strike-slip was probably the dominant faulting mechanism.

In total, surface waves from 60 events identified as being part of this swarm were observed at ALQ. In several cases, Love waves an order of magnitude smaller than those in Figure 2a and b, an $m_b = 4.2$ event, were recorded demonstrating the value of the horizontal components and how they enhance the detection capabilities of a single seismograph station.

This technique is now being applied to several earthquakes that occurred in central Asia between 1965 and 1969 and that appeared explosion-like on an M_s-m_b plot, where M_s is computed from observed Rayleigh wave amplitudes. From an examination of the horizontal component seismograms from several WWNSS stations, it is found that well developed Love waves with periods as long as 40 seconds are observed for several events after an azimuthal range of 100°. At many of these stations, the amplitude of the horizontal component Love waves was significantly greater than the amplitude of the vertical component of the Rayleigh waves.

The larger of the anomalous events, with a reported m_b value of 5.5, occurred as part of a sequence of seven events between 31 July and 2 August, 1965. Well developed long-period Love waves were observed at most WWNSS stations where any surface waves were observed for all seven of these

events. In particular, the WWNSS station at Chiang Mai, Thailand (CHG) recorded Love wave amplitudes averaging 2.5 to 3.0 times greater than the Rayleigh wave amplitudes for this sequence of events. M_S values calculated on the basis of Love wave amplitudes thus offers an additional tool in M_S-m_b discrimination between underground nuclear explosions and natural earthquakes. This observation is especially significant since CHG, in addition to being the site of a WWNSS station, is now a high-gain station as well, greatly enhancing the detection capabilities for both Rayleigh and Love waves.

B. Detection Capabilities of the VLP Stations

Recently the Seismic Discrimination Group at Lincoln Laboratory compiled a special listing of the occurrence of as many events as possible for the time period 20 February 1972 through 19 March 1972. Hereafter this special listing and the above 1 month time period will be referred to as the International Seismic Month (ISM). The final version of the ISM listing contains 996 entries identified on the basis of short-period body waves recorded on the various arrays (LASA, NORSAR, ALPA); the Canadian, Swedish, and United Kingdom seismograph networks; and the WWNSS stations. The ISM listing serves as an excellent data base to be used in the determination of approximate detection threshholds of the high-gain stations.

Figure 3 shows the percentage of reported events above the plotted magnitude for which surface waves were observed at one or more of the high-gain stations. Only shallow ($h < 100$ km) events which had 2 or more stations reporting a magnitude were used in this comparison. Note that surface waves were observed for 90% of the reported events of m_b

4.6 or greater. Half of the 10% of these events not observed were the result of masking by the coda of earlier larger events. Significantly, the largest single event not in coda for which surface waves were not observed was of m_b 4.8, and one additional event of m_b 4.7 was also missed. All the remaining events not in coda for which surface waves were not observed were of m_b 4.6 or less.

Two other important observations that are not obvious from Figure 3 come from the analysis involved in the preparation of this figure. They are the following:

1. Approximately 10% of the events observed at the deep stations EIL, OGD, and KON were observed on the basis of long-period Love waves only. The reason for restricting this statement to the deep stations is that the horizontal component seismographs at these sites operate with peak magnifications equivalent to those of the vertical component systems. In addition the low noise levels on the horizontal component seismograms from these three stations do not undergo any obvious diurnal variations as do the horizontal nosie levels at the other shallower sites (Murphy et al., 1972; Savino et al., 1972a and b).

2. Surface waves with periods between 30 and 50 seconds were recorded from more than 90% of the 465 observed events. This percentage is greater than that for the number of events for which surface waves with periods near 20 seconds were observed.

C. Detection Threshholds versus Epicentral Distance:

Detection threshholds for long-period surface waves as a function of epicentral distance were previously discussed by Savino et al. (1972b) and

Evernden et al. (1971) for a few of the original high-gain stations. The installation of additional high-gain stations and the availability of the ISM listing prompted us to reconsider this problem.

For this study all those events listed in the ISM as having a focal depth of 50 km or less, and assigned a body-wave magnitude (m_b), were considered. In Table I values of the 90% detection thresholds in two different 10° distances ranges are given in terms of m_b for 5 of the high-gain stations. Because of insufficient data at CTA and EIL in the 20° to 30° distance range threshhold values were instead determined in the 30° to 40° range at these two stations. From Table 1 we find that mean values of the 90% detection threshholds for surface waves range from m_b = 4.2 at 30° to about m_b = 4.7 at 90°. It should be noted that these threshhold values are based on visual analysis of seismograms and that the filtering techniques described by Choy and McCamy (1973) should lower these values by at least 0.2 m_b units.

A paper describing the results of the detection and discrimination capabilities of the high-gain stations based on the ISM listing is in preparation (Tatham and Savino, 1974).

D. <u>General Seismological Investigations</u>:

Various investigations employing both the analog and digital data from the high-gair stations include the following:

a) our investigations of the source (or sources) and behavior of long-period earth noise at the high-gain stations, particularly the experiment at OGD, have shown that earth noise levels between about 30 and 50 seconds are nearly the same at all these widely varying geographical locations. In addition, the system noise levels between 30 and 50 seconds are at least 15 dB below the levels of earth noise. Thus the recognition

of the source (or sources) of this earth noise, its effective wavelength, and temporal and geographical behavior could possibly indicate techniques that might result in further improvements in the detection capabilities of the high-gain stations. The experiment at OGD indicates that horizontal-component seismometers should be placed at depths of 150 to 200 m below the surface at a hard rock site to minimize the effects of moderate winds and atmospheric turbulence on S/N. Based on this same experiment, however, we conclude that vertical-component seismometers can be operated with very high recording magnifications at substantially shallower depths of burial at hard rock sites.

b) First motion determinations and fault plane solutions. The high-magnification data at long-periods are proving to be extremely valuable for the determination of the proximity of a particular station to a nodal plane, and thus the determination of fault plane solutions using long-period body waves.

c) A study of dc tilts associated with large ($M_S \geq 7.5$) earthquakes, earth tidal tilts, and background secular tilts observed on the displacement outputs at the high-gain stations. To date, dc tilts have been observed at CTA after a large ($M_s = 8.0$) New Guinea shock and at OGD after a $M_s = 7.6$ earthquake at Sitka, Alaska. Additional large earthquakes are being investigated and the observed dc tilts, as well as dc strains, will be compared with theoretical calculations.

d) Many seismic body waves are associated with rays which are not minimum travel time paths. Such arrivals contain pulse deformation due to a phase shift in each frequency component. For sufficiently high frequencies, the phase shift is $\pi/2$ and frequency independent. Hence, the original waveform is related to the distorted pulse via Hilbert

transformation. The distorting effect of a frequency-independent phase shift is successfully observed in seismograms from events in several regions. The data examined are long period ($T > 9$ seconds) and were taken from the high-gain stations and the WWNSS. They include deep earthquakes (depth > 500 km), in which a series of well separated S phases (S, sS, SS and sSS) are available. These show that the waveform of SS, which has been distorted in propagation through the Earth, can be derived from the waveform of sS, which is not distorted. SS and sS form a Hilbert transform pair. Shallow events, in which multiple S phases overlap, also exhibit behavior predicted by phase distortion. Rays critically reflected or refracted at a discontinuity in the Earth also suffer a constant phase shift, which in general can have any value. An important case is SKKS: its undistorted wave form resembles that of SKS, which has a minimum travel time path.

Without exception, all the distorted waveforms bear little or no resemblance to the original waveform. That is, neither the first arrival of energy nor the subsequent relative position of peaks and troughs on a distorted waveform appear at the ray theoretical times. Thus, $T-\Delta$ curves constructed by choosing arrival times to correspond to the first arrival of energy may be biased. Similarly, doubt is cast on differential travel times chosen from first motions, or from averaging several points on what appear to be corresponding peaks and troughs of two waveforms. Some of the rays most important to seismology, in which the distortion phenomenon occurs, include P and S (where $d^2T/d\Delta > 0$), PKP_{AB}, PP, SS, and SKKS. We find that removal of phase distortion in the data is computationally straightforward, and the resulting waveform may be

exploited to full advantage in correctly picking arrival times.

TABLE 1

90% surface wave detection thresholds (m_b)

	20° to 30°	30° to 40°	80° to 100°
CTA		4.0	4.9
EIL		4.2	4.9
ALQ	~ 4.2		4.4
KON	4.0		4.5
TLO	~ 4.5		4.7

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*Papers published or prepared under contract F44620-71-C-0082.

FIGURE CAPTIONS

Figure 1. Schematic representation of surface-wave radiation patterns for faulting mechanisms anticipated in the northern Gulf of California. Note the optimum azimuthal position to ALQ for discriminating between the two types of faulting.

Figure 2. a) Portions of ALQ seismograms showing surface waves from two swarm events. Recordings start at 02:34, with all components normalized to the same magnification.

b) The same data with horizontal components rotated into equivalent radial and transverse components. Note strong Love-wave motion on transverse component.

c) Same as Figure 2a - for portion of traces starting at 04:49.

d) Same as Figure 2b - for portion of traces starting at 04:49.

Figure 3. a) Histogram comparing the detection capabilities of each of the VLP stations with the ISM.

b) Histogram comparing the detection capabilities of the nine VLP stations during a quiet 48 hour time interval (left-hand side) and a 48 hour time interval during which masking is severe (right-hand side).

c) Histogram comparing the detection capabilities of the nine VLP stations for events of either shallow focal depths ($h \leq 50km$) or $h > 50km$.

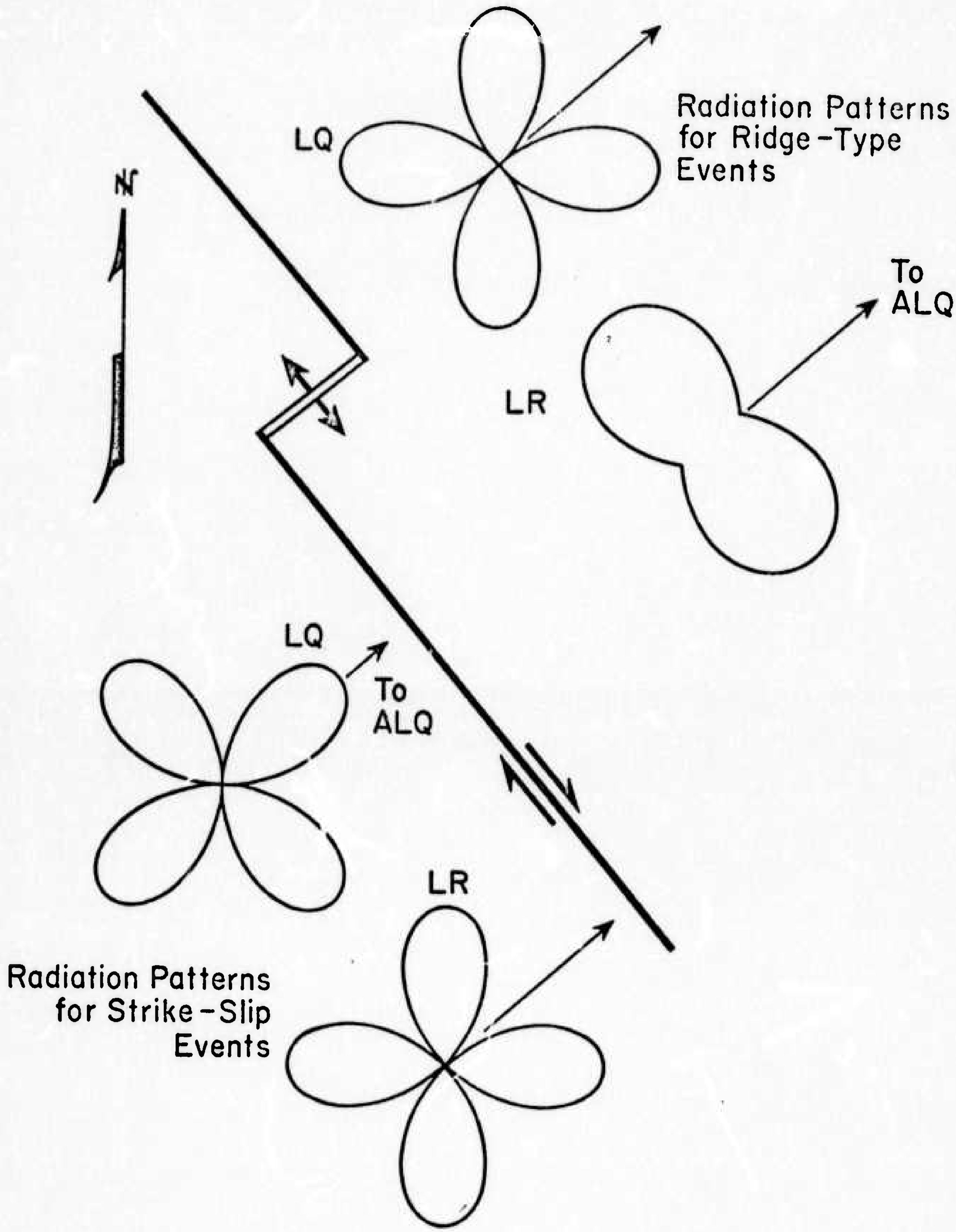
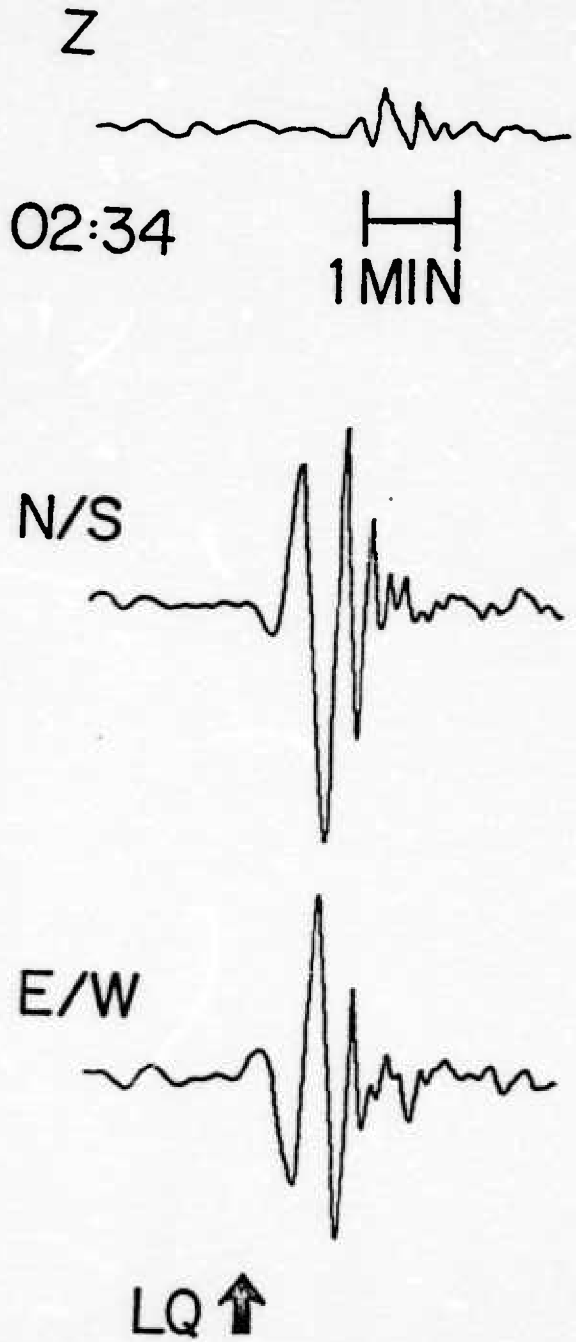
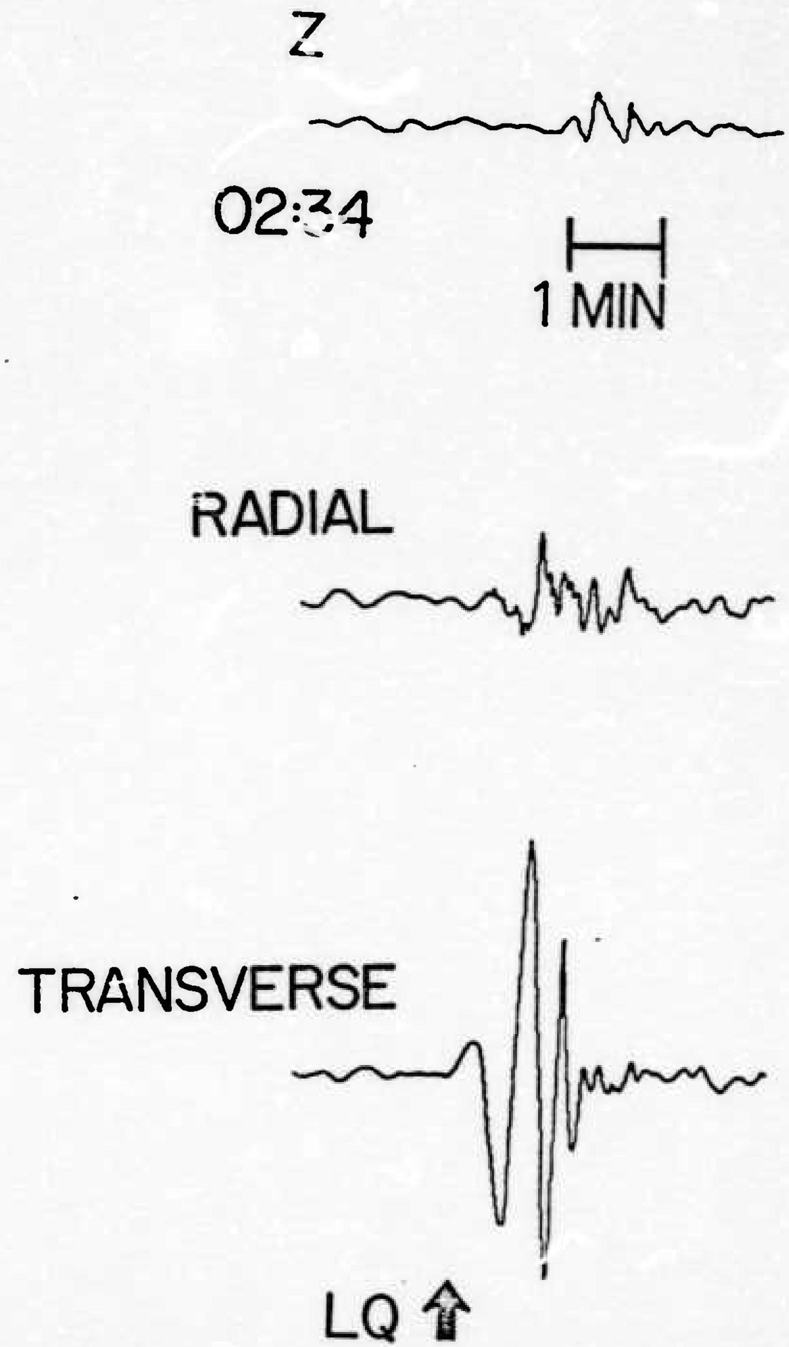

Radiation Patterns
for Ridge-Type
Events
LQ
N
To
ALQ
LR
LQ
To
ALQ
LR
Radiation Patterns
for Strike-Slip
Events

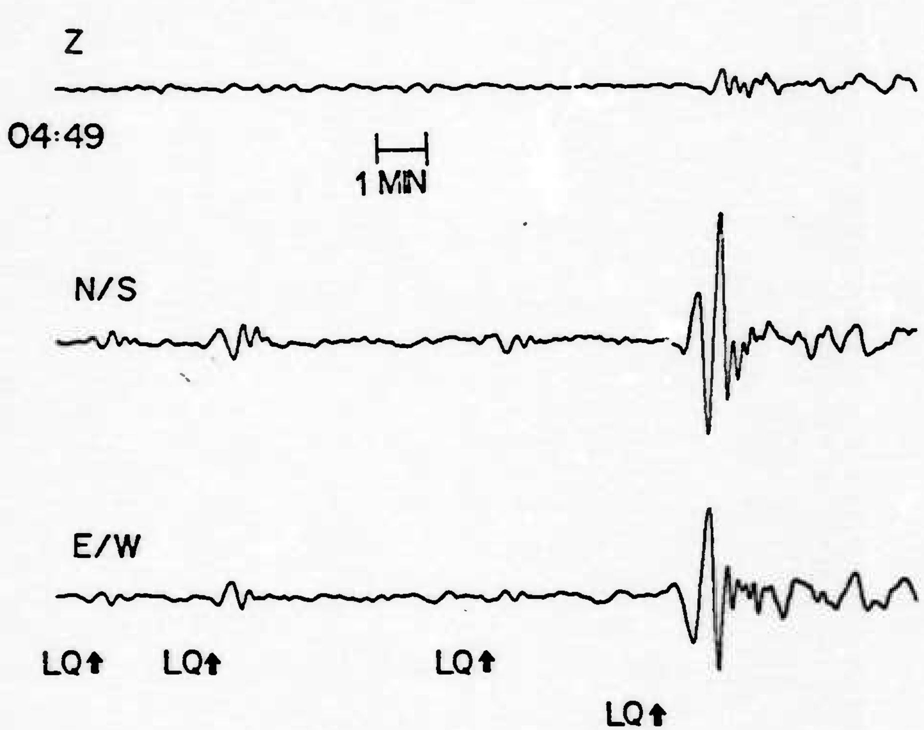
FIGURE 1



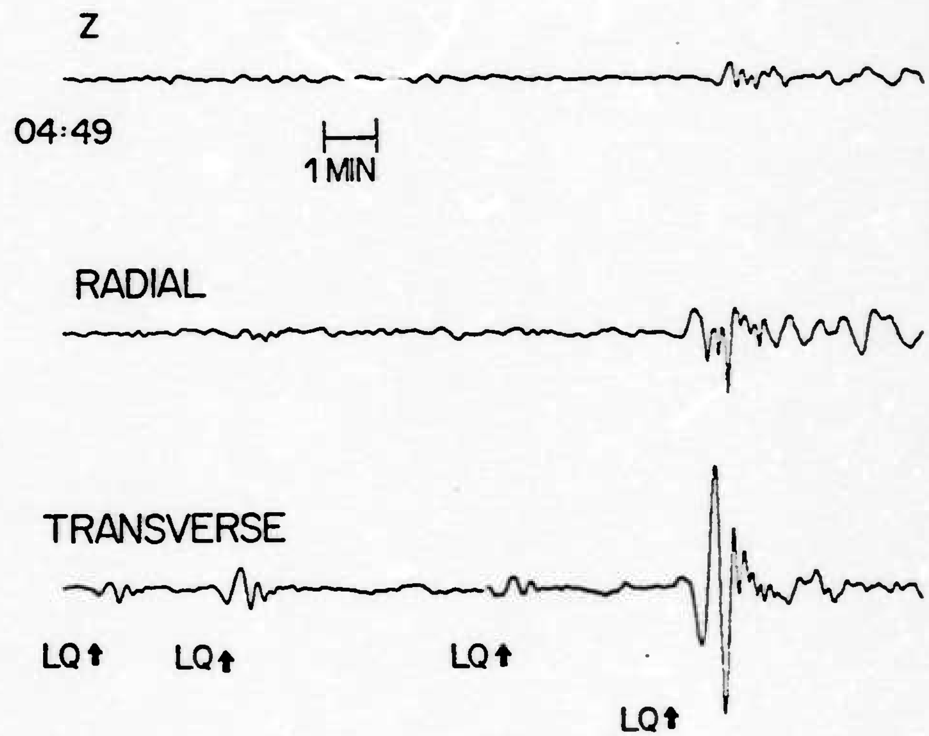
2a



2b


Z
04:49
1 MIN
N/S
E/W
LQ↑
LQ↑
LQ↑
LQ↑

2c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1 MIN
RADIAL
TRANSVERSE
LQ↑
LQ↑
LQ↑
LQ↑

2d

17.

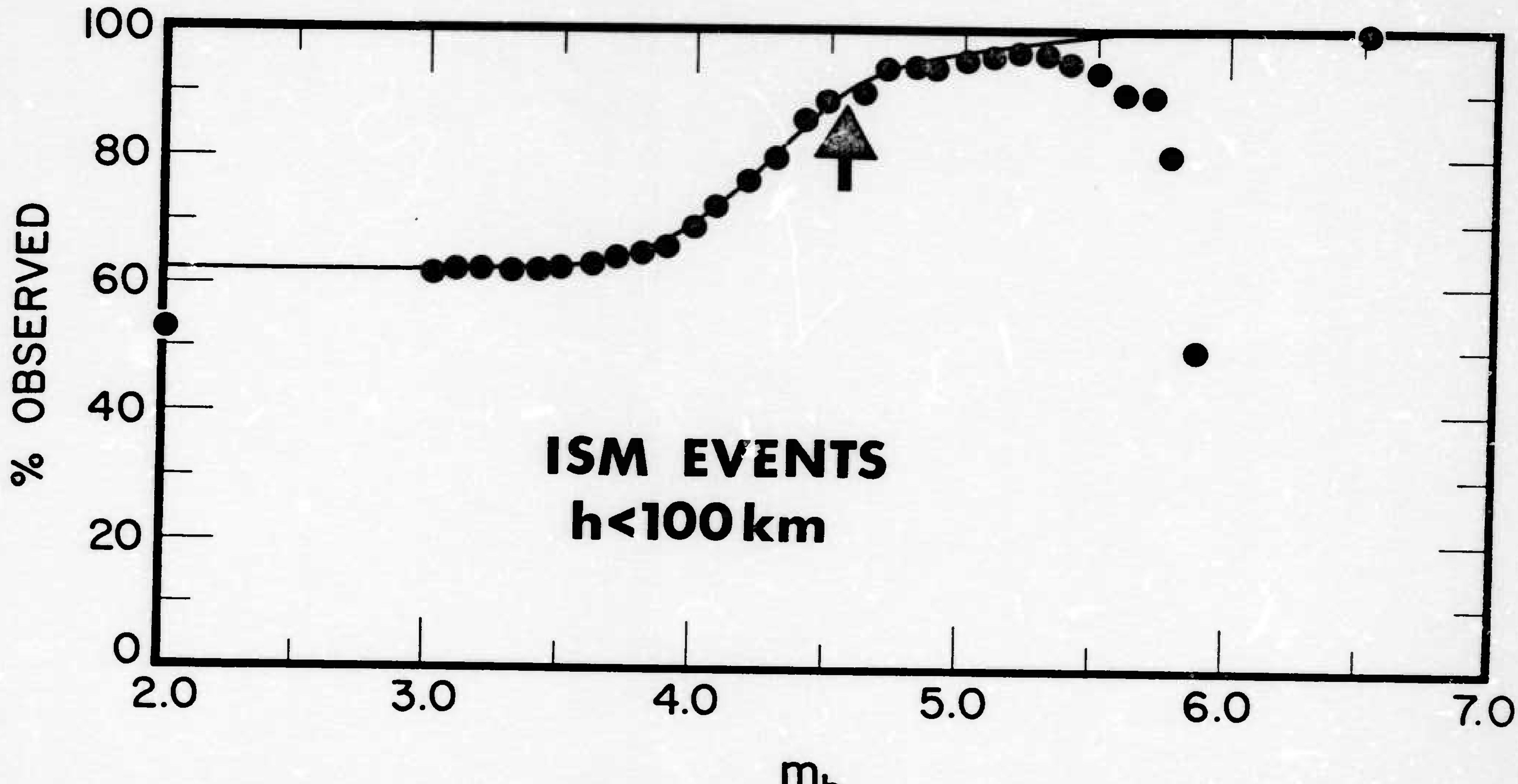

FIGURE 3

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